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RESEARCH ARTICLE

A Comparative Study of Image Processing Techniques for Javanese Ancient Manuscripts Enhancement

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ABSTRACT Digital preservation to preserve information in ancient manuscripts is often not optimal because of the object's condition, which has degraded over time. Therefore, quality enhancement is required through several image processing techniques to optimize the readability of the information within them. This study explores five types of filters, Gaussian Blur, Adaptive Thresholding, Canny Edge Detection, Morphology, and Sobel Algorithm, to address the readability challenges of three types of ancient Javanese manuscripts, *Serat Piwulang Cablaka, Serat Pakem Gancaripun Lelampahan,* and *Serat Piwulang Nulis*. This study evaluates how each filter enhances visual clarity while maintaining structural integrity using evaluation metrics such as the Structural Similarity Index Measure (SSIM) and Normalized Cross-Correlation (NCC). Based on the evaluation of the result, this study revealed that Gaussian Blur performed well, attaining an average SSIM value of 0.91, signifying its proficiency in preserving the original visual structure and texture. Furthermore, this study emphasizes the potential of combining Gaussian Blur with techniques like Adaptive Thresholding and Morphologyological operations to achieve an optimal balance between improving legibility and maintaining the authenticity of manuscripts.

INDEX TERMS Image processing, image denoising, thresholding, image edge detection, morphological operations, ancient manuscript.

I. INTRODUCTION

The preservation and improvement of the quality of cultural heritage, such as ancient manuscripts, is an important agenda for preserving historical knowledge for future generations. As one of the cultural heritage of the Republic of Indonesia, Javanese manuscripts provide important information, including cultural, religious, literary, and philosophical values that function as important resources that are very vulnerable to physical damage over time [1]. These manuscripts often present faded ink, fragile pages, and indistinct details due to environmental exposure, natural deterioration, and repeated handling [2]. These variables make it even harder for scholars to decipher and analyze the material in general and could have a resounding impact, with the very likely possibility of causing still further damage to the fragile, valuable manuscript [3]. Digital preservation is a potential alternative that allows for precise documentation and increased accessibility to these works while protecting the original assets [4]. Digitizing old manuscripts not only mitigates further physical degradation but also facilitates the dissemination of this knowledge to a broader audience [5]. This strategy allows cultural legacy to persist in a form less vulnerable to the ravages of time [1].

Digital preservation of Javanese manuscripts poses several challenges. Standard digital scanning and archiving processes sometimes inadequately capture these artifacts' subtle yet crucial properties [6]. Owing to the fragile nature of the

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manuscripts, hand preservation methods may sometimes lead to the loss of precise details [7]. Text and visuals may not preserve their inherent tones, soft textures, and nuanced contrasts, leading to diminished readability and precision. The digital representations may lack the requisite depth and clarity for accurate interpretation [8]. Therefore, further methods that can improve the quality of images and explain the information contained therein while maintaining the integrity of the structural elements of an ancient manuscript such as digital image processing techniques are needed to overcome this challenge [9].

Numerous prior studies have demonstrated the effectiveness of image-processing techniques for enhancing ancient manuscript collection. Methods such as Gaussian [10], [11], [12], Adaptive Thresholding [13], [14], [15], and Morphological Filters [16], have been widely used to reduce noise and restore some structural elements, making them essential tools for digital preservation. Other studies were also built by applying other data processing techniques, such as the Sobel, bilateral, median [16], and also Canny Edge detection [17], [18], [19]. These techniques solve frequent concerns with digitized manuscripts, and the integration of these filtering techniques with other image-processing methods offers the potential to create more robust solutions for digital preservation.

Based on these developments, the present study further advances the quality and readability of digitized Javanese manuscripts by applying and critically testing new approaches in image processing. These manuscripts, which are fragile cultural artifacts, often contain ink fade, contrasts in color, and structural degradation, which can make the accurate interpretation and analysis of their contents quite challenging [20]. Correspondingly, this paper compares some of the very crucial binarization techniques, such as adaptive thresholding and Canny Edge detection, together with filtering methods involving Sobel, Gaussian blur, and Morphology enhancement in finding the most suitable method for digital preservation, where cultural and structural integrity is maintained in manuscripts. Hence, this study will enable further digital cultural heritage preservation and open such documents for scholars, historians, and future generations by providing a sound solution to enhance such historical documents.

The structure of this research paper consists of several sections. Section II reviews previous research on manuscript preservation and image processing techniques. Section III describes the methodology of some of the technical processing applied for the implementation and comparison of five specific methods. Then, section IV will present the data results from each filter applied to ancient Javanese manuscripts. Then, section V discusses the advantages and limitations of each filter and their implications for future digital preservation methods. Finally, section VI provides a conclusion, highlighting the research's contribution to cultural heritage preservation.

II. RELATED WORK

A. MANUSCRIPT PRESERVATION

Ancient manuscripts are a historical heritage that is a very valuable storehouse of knowledge and can provide a glimpse of past civilizations. These ancient manuscripts include a variety of materials ranging from literary works to religious texts and historical records [21]. The preservation of ancient manuscripts is challenged by the diverse materials used, such as parchment and papyrus, each requiring specific conservation strategies. The main problem in preserving ancient manuscripts is in the process of making the characters contained therein recognizable. However, most such manuscripts often appear degraded, improper to read and study due to their age factor and lower quality manufacturing and presentation [17]. Fragile media, loss of fine details, and the use of ancient scripts that are mostly no longer used in daily activities such as ancient writings in Javanese manuscripts also present serious challenges in extracting the information contained therein [21].

To overcome these challenges, researchers have explored various preservation methodologies to obtain effective textual information extraction techniques for degraded ancient manuscripts [22]. Over time, many experts have shifted from traditional preservation methods to digital-based preservation methods to overcome the limitations of this problem. Unlike traditional preservation techniques that risk damaging fragile materials, digital preservation methods are an effective way to create something durable [23], [24], produces more accurate information [25], make authentic and provable data and information because it is obtained through a series of systematic information [26], and also can be shared and utilized widely without damaging the original artifact [27].

However, digital preservation methods have their challenges, especially when used for complex artifacts. Scanning ancient manuscripts often fails to capture the intricacy of faded details, as well as the subtle textures and contrasts present on the page. Digital methods offer several techniques such as image augmentation that improve legibility and preserve detail [28], but require careful and precise execution of the techniques to ensure authenticity. Experts in the field have observed that effective preservation beyond simple digitization is advanced image processing techniques, as they can maintain visibility of the most important qualities of the data to maintain the integrity of the original artifact [29], [30]. In recent years, researchers have increasingly combined digitization with specialized filters to address the preservation challenges presented by ancient manuscript collections.

B. IMAGE PROCESSING TECHNIQUES

Image processing techniques are one of the popular techniques in improving the readability of ancient manuscript information. Not only is it able to improve the quality [12], [31], but also includes techniques that are beneficial for restoring significant aspects of a picture that has been

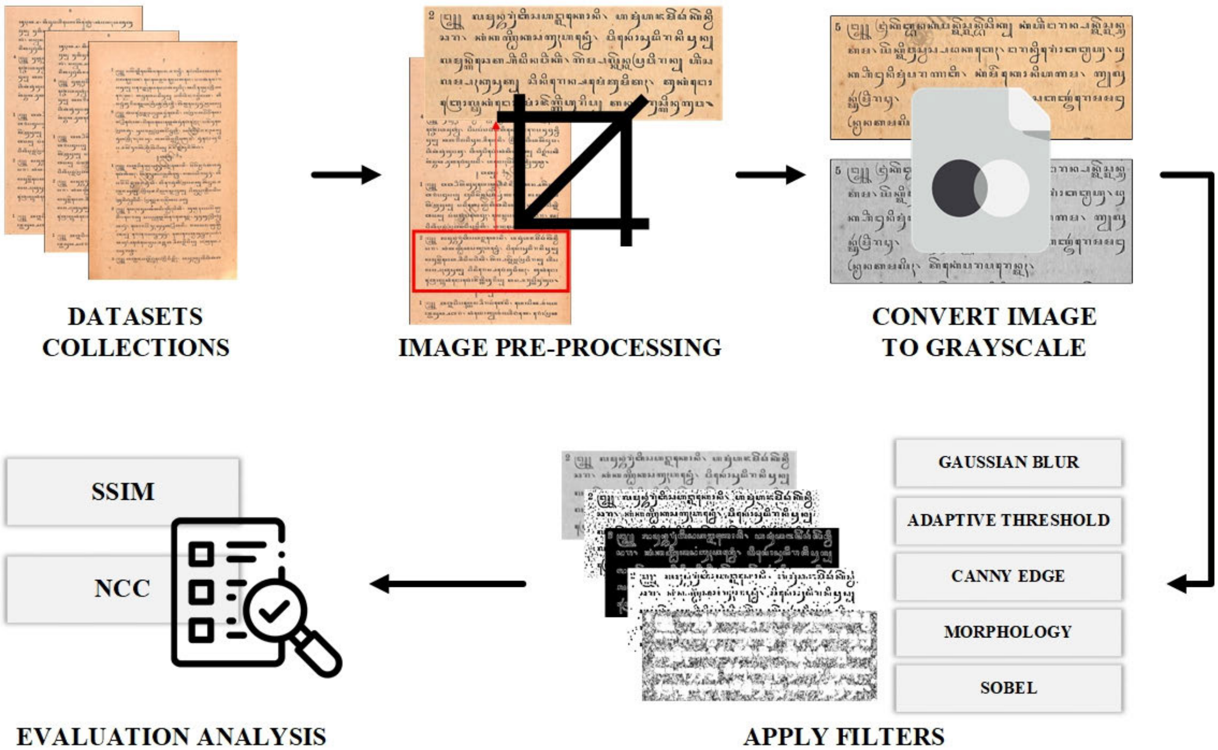

FIGURE 1. Workflow diagram of proposed method.

compromised owing to various situations, such as text degradation [10], [32]. In the previous study, Techniques such as binarization and adaptive thresholding have been widely used to improve the readability of ancient texts, such as the adaptive binarization technique applied by Yahya et al. to enhance images in ancient Malay manuscripts [33]. Similarly, several techniques such as Souvola, Niblack, and Adaptive thresholding were also used in comparison for image enhancement in the restoration process of ancient Kannada handwritten palm leaf manuscripts [34]. A modified whale optimization algorithm was also shown to maximize adaptive thresholding for the restoration of Indian palm leaf manuscripts [35].

Filtering methods represent another critical aspect of image enhancement for ancient manuscripts. In previous research, Tsvetkova et.al. adopted several techniques such as gamma correction, Contrast Limited Adaptive Histogram Equalization (CLAHE), and Gaussian smoothing to study palimpsests [36]. Similarly, this Gaussian filter was used to analyze ancient manuscripts in India [11]. In another study, the Gaussian filter was also adopted by Jayanthi and Maheswari and compared with several other image processing methods such as Sobel, Bilateral, Median, and Morphological [16], the result shows the unique strengths of each technique.

Alongside the aforementioned processing techniques, edge detection methods, such as Canny Edge detection are employed to improve ancient manuscript images [19]. This method, which is a combination of several processes such as Gaussian smoothing, excels at identifying and preserving fine structural details, such as text lines and decorative elements, which are often lost in damaged manuscripts. This technique can also be applied with other techniques, such as classification techniques [17], [18]. Nonetheless, this strategy has not been extensively utilized in the studying of ancient manuscripts including distinctive characters like Javanese, rendering this technique particularly intriguing for further investigation. This work utilized five image processing approaches derived from prior research, including Gaussian blur, adaptive thresholding, Canny Edge detection, Morphological operations, and Sobel filters. each technique offers unique advantages for enhancing specific elements of the manuscripts.

III. METHODS

This paper outlines a detailed and systematic method for improving the quality and readability of ancient manuscript images through advanced image processing techniques. This strategy guarantees a fair representation across many manuscripts, allowing for a thorough evaluation of how well image processing methods improve readability while maintaining structural integrity. The high-resolution digitization of each sample allowed for capturing minute details essential for precise processing and comparison.

The proposed workflow, depicted in Figure 1, comprises a series of well-defined steps aimed at achieving optimal clarity, preserving structural integrity, and ensuring reproducibility. The methodology emphasizes the integration of preprocessing, filtering, and metric evaluation to address challenges such as noise, faded ink, and structural degradation commonly observed in historical documents. The methodology utilizes SSIM and NCC as evaluation metrics, yielding strong, quantitative insights into the efficacy of each filter.

A. DATASET COLLECTIONS

The dataset collection phase is the preliminary stage of digital image processing, encompassing the gathering of ancient Javanese manuscript images from reliable and reputable sources. This study encompasses manuscripts including *Serat Piwulang Cablaka (Cablaka)* [37], *Serat Pakem Gancaripun Lelampahan (Gancaripun)* [38], and *Serat Piwulang Nulis (Piwulang)* [39]. This rare manuscript has been converted from analog to digital format using a Canon EOS R50 Camera which is part of the collection at the Gadjah Mada University Library, Indonesia. All datasets are ancient manuscripts with cultural value that have degraded over time.

B. IMAGE PREPROCESSING

During the preprocessing step, each manuscript image was cropped to emphasize Regions of Interest (ROI) that included critical information, like text or ornamental features. As shown in Figure 2, this image-cropping process produces four different images from each title of the manuscript collection which will be processed in the next stage.

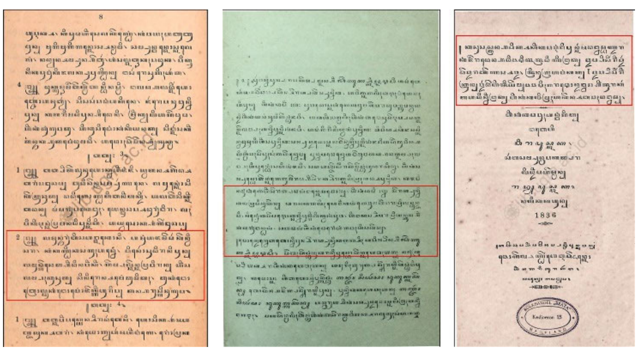

FIGURE 2. Research's Region of Interest (ROI) from javanese ancient manuscript datasets. a) Serat piwulang cablaka (Cablaka) [37], b) Serat pakem gancaripun lelampahan (Gancaripun) [38], c) Serat piwulang nulis (Piwulang) [39].

C. CONVERT IMAGE TO GRAYSCALE

Each image is converted to grayscale to standardize the image processing workflow, reducing its color information to a single intensity channel. This transformation simplifies the data structure, emphasizing pixel intensity, which is crucial for processing ancient manuscripts where textual and structural details outweigh the importance of color.

In this model, each pixel in the image, initially characterized by three color components—Red (R), Green (G), and Blue (B)—is transformed into a single grayscale intensity. The grayscale value for a pixel,Gray (i, j), calculated as a weighted average of the RGB components. The weights, denoted as κ_1, κ_2, and κ_3, correspond to the relative contributions of the R, G, and B channels, respectively, and satisfy the condition $\kappa_1 + \kappa_2 + \kappa_3 = 1$ [40]. The formula for the grayscale value is given by (1):

$$\text{Gray}\,(i, j) = \kappa_1 \cdot R\,(i, j) + \kappa_2 \cdot G\,(i, j) + \kappa_3 \cdot B\,(i, j) \tag{1}$$

Grayscale conversion improves the contrast of subtle text elements and lowers computational complexity, allowing subsequent filters to operate on a uniform and streamlined dataset. This step is particularly valuable for historical manuscripts, as natural discoloration of ink and background can interfere with color-based processing methods.

D. APPLY FILTERS

At this step, various image processing methods are applied to enhance the quality of grayscale images, including Gaussian blur, adaptive thresholding, Canny Edge detection, Morphological operations, and the Sobel algorithm. Each of these filters is designed to address specific challenges commonly found in ancient manuscripts. Gaussian blur smoothens textures and reduces noise, while adaptive thresholding dynamically separates text from the background to improve clarity. Canny Edge detection highlights fine structural details and edges, making subtle features more discernible. Morphological operations repair fragmented text and remove minor noise, restoring continuity in damaged areas. Finally, the Sobel Algorithm enhances intensity gradients, improving edge clarity and definition. By combining these filters, the study effectively tackles issues such as faded ink, structural damage, and inconsistent textures, ensuring improved readability and preservation of historical documents.

Gaussian blur is a smoothing filter that applies a Gaussian function to reduce high-frequency noise in an image, which is particularly useful for enhancing aged manuscripts. By averaging pixel values within a neighborhood, Gaussian Blur reduces minor imperfections caused by ink smudges, scratches, or scanner noise, while preserving the overall structure of text and illustrations. Mathematically, Gaussian Blur is represented by the convolution of the image with a Gaussian kernel [41], defined by (2):

$$G\,(x, y) = \frac{1}{2\pi\sigma^2} e^{-\frac{x^2+y^2}{2\sigma^2}} \tag{2}$$

where $G\,(x, y)$ is the Gaussian function applied to pixel (x, y), and σ is the standard deviation of the Gaussian distribution, which controls the level of blur [42].

Adaptive thresholding is a simple thresholding technique that compares the current pixel value of the image with the mean or average of all nearby pixels [16]. The current pixel is set to black when the value is less than the mean value, and to white otherwise, which is also known as binary [15]. This method is perfect for manuscripts with uneven or fading ink since it improves contrast and helps distinguish text from the backdrop in low-contrast images.

The adaptive threshold $T(x, y)$ for each pixel (x, y) is computed as shown in (3):

$$T(x, y) = \frac{1}{n} \sum\nolimits_{i,j \in \mathcal{N}(x,y)} I(i, j) - C \tag{3}$$

where $I(i, j)$ are the intensity values of pixels within the neighborhood $\mathcal{N}(x, y)$ of pixel (x, y), n is the number of pixels in the neighborhood, and C is a constant subtracted to fine-tune the threshold [15]. The resulting binary image $I_{\text{threshold}}$ shown in (4):

$$I_{\text{threshold}}(x, y) = \begin{cases} 0, & \mathit{If}\ I(x, y) < T(x, y) \\ 255, & \mathit{If}\ I(x, y) \geq T(x, y) \end{cases} \tag{4}$$

Adaptive Thresholding is effective in isolating faded or fragmented text from noisy or patterned backgrounds and is commonly used in manuscripts with uneven inking or discoloration due to aging.

Canny Edge detection is an advanced multi-step technique aimed at finding edges by recognizing areas in an image with abrupt intensity variations [43]. This technique can be applied to detect edges of text in degraded ancient manuscripts. This algorithm involves noise reduction, gradient calculation, non-maximum suppression, and multiple thresholding to detect edges accurately.

1. Gaussian smoothing: First, Gaussian smoothing is applied to the image to reduce noise, as represented by the Gaussian Blur described previously.
2. Gradient calculation: The gradient amplitude of the pixel is determined by calculating the first derivative in both the x and y [44]. Equation (5) directions using Sobel operators S_x and S_y:

$$G_x(x, y) = I(x, y) * S_x \text{ and } G_y(x, y) = I(x, y) * S_y \tag{5}$$

where (G_x) and (G_y) are the gradients in the x and y directions. The gradient magnitude and direction are then calculated as per (6) and (7):

$$G(x, y) = \sqrt{G_x(x, y)^2 + G_y(x, y)^2} \tag{6}$$

$$\theta(x, y) = tan^{-1}\left(\frac{G_y(x, y)}{G_x(x, y)}\right) \tag{7}$$

3. Non-Maximum suppression and double thresholding: This step ensures that only the most significant edges remain [44], producing a binary edge map that captures the structural boundaries within the manuscript.

Morphological (Morph) are image processing techniques used to enhance or modify the structure of objects within an image, particularly in cases where thresholding or other preprocessing steps may have eroded or added pixels to characters [16]. For manuscript preservation, dilation and erosion are two fundamental operations that help improve text clarity by strengthening the contrast and removing small noise artefacts. Dilation expands the boundaries of text elements, filling gaps in letters or symbols, while erosion shrinks boundaries, removing extraneous noise.

1. Dilation: The dilation operation increases the pixel intensity within a defined neighborhood around each pixel, with a structuring element B. Dilation is represented at (8):

$$I_{dilated}(x, y) = \max_{(i,j)\in B} I(x + i, y + j) \tag{8}$$

2. Erosion: Conversely, erosion decreases pixel intensity within the defined neighborhood, helping remove unwanted noise. Erosion mathematically shown in (9):

$$I_{eroded}(x, y) = \min_{(i,j)\in B} I(x + i, y + j) \tag{9}$$

By combining these operations (e.g., through opening or closing), Morphology filters can selectively emphasize or suppress features in a manuscript image, making them useful for improving text visibility and reducing background noise without compromising fine details.

Sobel filter is a directed edge detection filter that calculates picture gradients to accentuate edges in particular orientations, hence improving textual and structural features [42]. The Sobel filter employs convolution masks to estimate The derivative of image intensity in both horizontal and vertical directions.

The Sobel operator is defined by two kernels S_x and S_y for the x− and y− directions [45], respectively (10):

$$S_x = \begin{bmatrix} -1 & 0 & 1 \\ -2 & 0 & 2 \\ -1 & 0 & 1 \end{bmatrix}, \quad S_y = \begin{bmatrix} -1 & -2 & -1 \\ 0 & 0 & 0 \\ 1 & 2 & 1 \end{bmatrix} \tag{10}$$

The gradients in each direction are calculated as shown in (11):

$$G_x(x, y) = I(x, y) * S_x, G_y(x, y) = I(x, y) * S_y \tag{11}$$

The magnitude of the gradient is then obtained by (12):

$$G(x, y) = \sqrt{G_x(x, y)^2 + G_y(x, y)^2} \tag{12}$$

This magnitude map emphasizes the edges of the manuscript image, enhancing the outlines of the text and structural elements with increased contrast.

E. EVALUATION ANALYSIS

After applying the filters, the final step involves a comprehensive evaluation analysis of the recorded Structural Similarity Index Measure (SSIM). It is a sophisticated metric for evaluating image quality, focusing on perceptual differences between two images by analyzing luminance, contrast, and structural information [46]. It was developed as a superior alternative to traditional pixel-based error metrics like Mean Squared Error (MSE), offering a more human-centric approach [47]. By comparing the structural information embedded in an image, SSIM offers a more human-centric approach, which is particularly advantageous when dealing with intricate images like ancient manuscripts. SSIM's components luminance, contrast, and structure each designed to reflect how closely the image features align with human visual perception. According to [46], SSIM is expressed as shown in (13):

$$SSIM\ (x, y) = \frac{(2\mu_x\mu_y + C_1)\,(2\sigma_{xy} + C_2)}{\left(\mu_x^2 + \mu_y^2 + C_1\right)\left(\sigma_x^2 + \sigma_y^2 + C_2\right)} \tag{13}$$

where μ_{x} and μ_{y} are the mean pixel values, σ_{x}^2 and σ_{y}^2 are the variances, and σ_{xy} is the covariance of the images x and y, with C_1 and C_2 being small constants to avoid division by zero [48].

SSIM has become especially popular in cultural heritage preservation as it enables the assessment of image quality with a focus on the structural fidelity of the original manuscripts, where the visual authenticity of the content is critical. In particular, for ancient texts, SSIM ensures that both the typographical structure and any ornamentation or faded details are preserved, making it a powerful tool in the restoration process.

Besides the commonly used SSIM metric, this study also adopts another evaluation metric, specifically Normalized Cross-Correlation (NCC). NCC is another image similarity metric that measures the similarity between two images based on pixel intensity correlation [49]. In image processing, NCC is commonly used for tasks such as image registration, where precise alignment of images is required, particularly when dealing with historical documents or scanned manuscripts. Unlike SSIM, which focuses on structural similarity, NCC is based purely on the correlation of pixel intensities, making it particularly useful when comparing images that have undergone minor transformations, such as noise removal, contrast adjustment, or minor rotation. The NCC value ranges from -1 to 1, with 1 indicating a perfect match, 0 indicating no correlation, and values closer to -1 suggesting a strong inverse relationship [50]. The mathematical formula for NCC is shown in (14):

$$NCC\ (x, y) = \frac{\sum_{i=1}^{n} (x_i - \bar{x})\,(y_i - \bar{y})}{\sqrt{\sum_{i=1}^{n} (x_i - \bar{x})^2 \sum_{i=1}^{n} (y_i - \bar{y})^2}} \tag{14}$$

where $\mathrm{x}_{\mathrm{i,j}}$ and $\mathrm{y}_{\mathrm{i,j}}$ represent the pixel intensities at position (i, j) for the images x and y, and μ_{x} and μ_{y} are the mean values of the images [49]. NCC is particularly valuable in the context of manuscript preservation as it can be used to assess the effectiveness of image enhancement techniques, ensuring that any changes made to the image (such as improving legibility or removing noise) retain the original structure and meaning of the manuscript. Its application has been critical in projects where ancient texts are being restored digitally, as it verifies that the enhanced image is as close to the original as possible without distorting the manuscript's historical value. NCC has been effective in aligning images for comparison, but its performance may degrade when dealing with highly degraded or fragmented manuscripts, where subtle variations in text or ornamentation can lead to misalignments.

Furthermore, the following scatter plot in this study provides intuition regarding the relationship between two evaluation metrics, with SSIM values on the x-axis and NCC values on the y-axis. This gives a clear view of the performance of each filter for all images intuitively. Filters that achieve high scores in both metrics will be in the upper-right quadrant, reflecting a balance between structural preservation and intensity correlation. The scatter plot further develops the tendency of compromise between the two variables of readability and structural fidelity. This helps give clues as to how best to filter and optimize the filtering process.

IV. RESULTS

A. DATASETS AND EXPERIMENTAL PREPARATIONS

The datasets in this study are a collection of ancient Javanese manuscripts obtained from the Rare collection of the Gadjah Mada University Library, Indonesia, and have undergone some degradation. As seen in the sample in Figure 3, the dataset includes three book titles. First, *Serat Piwulang Cablaka*(Figure 3a) [37], which is a manuscript that is more than a century old and is estimated to have been produced in 1912, during the Dutch colonial period. This manuscript contains life lessons for humans from a religious perspective.

As shown in Figure 3b, the second dataset is the Serat *Serat Pakem Gancaripun Lelampahan*, [38] produced in 1879, which contains information about twenty-three wayang sketches (*wayang lakons)* that are common in wayang-poerwa performances in Java. This manuscript consists of two languages, Javanese and Dutch. However, this study focuses on the Javanese script section. The last dataset, as depicted in Figure 3c, Serat Piwulang Nulis, is a Javanese literary book about writing lessons produced in 1836. Hereafter, four examples were carefully selected for each type of manuscript, considering the type's historical value and the range of degradations present, including paper deterioration and ink fading.

Subsequently, to thoroughly assess the proposed method, a total of twelve images were tested using five types of image processing techniques. All images were processed on a PC running Windows 10 Pro OS version 22H2 with 32G RAM and AMD Ryzen 7 3700X 8-Core Processor. In this research, the setup for the computing environment with Python and Jupyter Notebook is made with the help of essential libraries such as OpenCV, NumPy, Matplotlib, and scikit-image. Images of manuscripts are situated in the input folder, whereas the processed results will be saved in the output folder. Each image is converted to grayscale to simplify the data and focus on text and structure. Five processing techniques are applied. Each technique is measured by the SSIM for structural similarity and NCC for intensity similarity. The results are analyzed to determine the best technique to improve the quality of the manuscript images while maintaining their historical authenticity.

B. EXPERIMENTAL RESULT

Based on testing five image processing techniques in this study, the Gaussian Blur Results in Figure 4a show a clear smoothing effect, with a significant reduction in background

FIGURE 3. **Sample of the original javanese ancient manuscript datasets. a) Serat piwulang cablaka, b) Serat pakem gancaripun lelampahan, c) Serat piwulang nulis.**

noise, where some stain spots on the paper are disguised. However, the benefits of this smoothing slightly reduce the details of the Javanese characters, making certain intricate parts less visible. Meanwhile, the adaptive threshold test results in Figure 4b indicate its effectiveness in distinguishing Javanese characters from the paper as the background. However, the binarization error in the background due to the degradation condition of the paper which has many stains and also uneven textures produces a lot of noise around the identified Javanese characters.

Meanwhile, the results of applying the Canny Edge detection image processing technique in Figure 4c which emphasizes text boundary detection and structural details have produced an accurate edge map. This approach efficiently highlights every detail of the curve of the Javanese characters, making it suitable for manuscripts with intricate ornaments or line structures. However, certain non-text elements are identified as edges and have the potential to cause foreign interference so further processing is needed. Next, in Figure 4d, the results of applying Morphology with the application of dilation and erosion techniques are quite efficient in explaining fragmented text. The combination of these two processes is optimal for repairing gaps in disturbed text. The results of this technique look similar to the adaptive Threshold method, but the noise produced is much less. However, some important details in the characters are also reduced in this test.

The last test result as in Figure 4e is the result of applying the Sobel method. The application of this algorithm to the image of an ancient Javanese manuscript successfully highlights the edges of the manuscript text with a fairly clear contrast between the writing and the background. However, the results show that some texts are detected imperfectly due to noise or random patterns in the background that are also identified as edges. This results in some parts of the text looking disjointed and less sharp.

In summary, Gaussian blur and Morphology are proficient in noise reduction and text restoration, while the adaptive threshold and the Sobel algorithm effectively enhance text readability by augmenting contrast. Simultaneously, the Canny Edge detection enhances the visibility of intricate structures, rendering it appropriate for sophisticated analysis or pattern recognition. The combination of these methodologies can yield enhanced outcomes in the digitization and conservation of historical writings.

C. METRICS EVALUATION

The evaluation of the SSIM metrics for five kinds of image processing techniques applied to ancient Javanese manuscript images, *Cablaka, Gancaripun,* and *Piwulang*, demonstrate the efficacy of each method in preserving structural consistency. As indicated in Table 1, the Gaussian blur consistently achieves high SSIM ratings, particularly for images like *Gancaripun* and *Piwulang,* with values ranging from 0.95 to 0.97. These values demonstrate that Gaussian blur preserves a high degree of structural similarity to the source manuscript images, rendering it suitable for applications necessitating true texture and structural features. The elevated SSIM value of gaussian blur signifies its efficacy in mitigating noise while maintaining the primary characteristics of the manuscript, including character outlines and intricate details, without altering the historical integrity of the text.

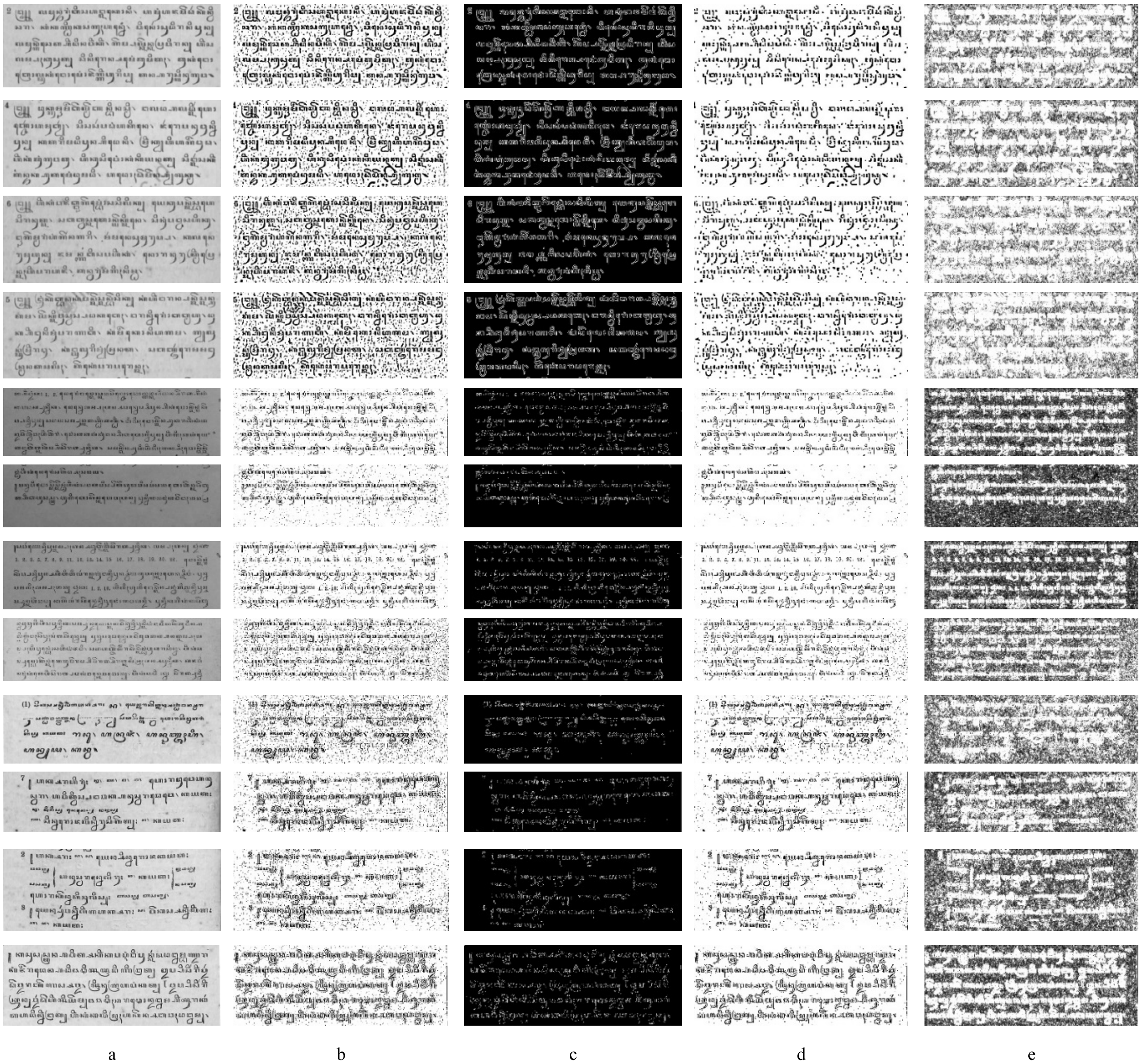

FIGURE 4. **Image processing result using, a) Gaussian blur, b) Adaptive thresholding, c) Canny edge, d) Morphology, and e) Sobel algorithm.**

Unlike the Gaussian blur filter, the Canny Edge and Sobel algorithm yield very low or even negative SSIM values, indicating substantial alterations in image structure. With SSIM values often close to 0 and some obtaining -0.01, Canny Edge focuses heavily on edge detection, capturing only the high-contrast boundaries while discarding subtler textural elements. Similarly, the Sobel algorithm yields minimal SSIM values, signifying a drastic departure from the original structure due to its emphasis on gradient changes. These filters are therefore less suited for preserving the overall integrity of the manuscript and may be more applicable in tasks that require boundary enhancement rather than structural retention.

In contrast, Table 1 shows the Morphology filter produces SSIM values between 0.54 and 0.76, signifying a compromise between structural preservation and augmentation. The Morphology filter preserves a certain level of structural resemblance while concurrently augmenting particular attributes of the manuscript, like line thickness. This positions it as a viable option for enhancing text readability while minimally modifying the original structure.

Simultaneously, as shown in Table 1, the adaptive threshold filter has moderate SSIM values, generally ranging between 0.32 and 0.57. This filter provides enhanced contrast between the text and background, beneficial for increasing readability, particularly in faded sections of the manuscripts.

Nonetheless, the trade-off associated with the adaptive threshold is a compromise in structural fidelity, as the filter emphasizes contrast enhancement at the expense of preserving original structural details. The SSIM values for the *Piwulang* manuscript are approximately 0.52, indicating that although the filter enhances text clarity, it may obscure more subtle characteristics of the manuscript. This filter is thus suitable for preprocessing tasks where readability takes precedence over precise structural preservation.

TABLE 1. SSIM metrics.

Datasets	Gaussian Blur	Adaptive Threshold	Canny Edge	Morpho logy	Sobel
Cablaka1	0.82	0.39	0.01	0.62	-0.04
Cablaka2	0.82	0.41	0.01	0.64	-0.04
Cablaka3	0.82	0.32	0.01	0.55	-0.03
Cablaka4	0.82	0.33	0.01	0.54	-0.03
Gancaripun1	0.96	0.50	-0.01	0.67	0.00
Gancaripun2	0.97	0.52	0.00	0.69	0.01
Gancaripun3	0.96	0.54	-0.01	0.70	0.00
Gancaripun4	0.95	0.44	-0.01	0.68	-0.02
Piwulang1	0.95	0.41	0.00	0.68	0.01
Piwulang2	0.97	0.52	0.01	0.72	0.02
Piwulang3	0.97	0.53	0.00	0.75	0.02
Piwulang4	0.96	0.57	0.00	0.76	0.02

In comparison to the SSIM metric, the NCC measure shows higher-quality evaluation results across diverse data processing applications. Table 2 indicates that Gaussian blur offers exceptional performance in NCC, achieving values between 0.97 and 0.99, particularly in the *Piwulang* and *Gancaripun* images. The elevated NCC scores indicate that Gaussian blur maintains structural similarity and a robust spatial correlation with the images from the original article. Gaussian blur serves as an ideal filter for archive and preservation endeavors, where superior visual fidelity and minimal distortion are paramount.

In addition, as shown in Table 2, the adaptive threshold filter exhibits moderate NCC values, generally ranging between 0.66 and 0.83. This range indicates that Adaptive Threshold can enhance text contrast and legibility without deviating too far from its original spatial arrangement. For example, the *Piwulang* image with an adaptive threshold achieves NCC values up to 0.76, which underscores the filter's efficacy in enhancing text contrast while minimally affecting spatial configuration.

On the other hand, the Canny Edge detection and Sobel algorithm show negative values, while Canny Edge frequently falls below -0.27 and Sobel often falls below -0.46 in some images, as it is in the *Gancaripun* and *Piwulang*sets. This strong negative correlation implies a rather different texture and spatial structure compared to the originals since these filters usually emphasize edges and high-contrast gradients at the expense of textual fidelity. The Canny Edge and Sobel representatives are not very good with maintaining original manuscript integrity because they drastically change

TABLE 2. NCC metrics.

Datasets	Gaussian Blur	Adaptive Threshold	Canny Edge	Morpho logy	Sobel
Cablaka1	0.88	0.72	-0.19	0.73	-0.27
Cablaka2	0.88	0.73	-0.19	0.73	-0.28
Cablaka3	0.87	0.66	-0.18	0.68	-0.23
Cablaka4	0.87	0.66	-0.17	0.67	-0.24
Gancaripun1	0.97	0.82	-0.32	0.87	-0.45
Gancaripun2	0.97	0.76	-0.34	0.85	-0.42
Gancaripun3	0.97	0.83	-0.32	0.88	-0.46
Gancaripun4	0.97	0.73	-0.31	0.80	-0.36
Piwulang1	0.97	0.66	-0.31	0.77	-0.26
Piwulang2	0.99	0.69	-0.27	0.79	-0.30
Piwulang3	0.99	0.71	-0.29	0.81	-0.32
Piwulang4	0.99	0.76	-0.28	0.86	-0.35

the visual structure and perhaps will be more useful for specialized jobs such as identifying boundaries or testing the state of deterioration. Morphology is mostly promising, with NCC results between 0.67 and 0.88, showing its ability to improve the contrast of some features within a relatively small deviation on the original spatial structure, hence proving useful as filtering under certain conditions that one might have to enhance any particular detail in a given manuscript.

To better understand the correlation or relationship between the two metrics, this study also constructed a scatter plot, as shown in Figure 5, to illustrate the performance of each filter in maintaining the SSIM and NCC values for various image filters applied to ancient Javanese manuscript images. Each filter influences the manuscript's structural integrity and visual correlation in distinct ways, suggesting their suitability for specific image-processing objectives. SSIM measures the structural similarity between the filtered image and the original, while NCC indicates the correlation in texture and contrast.

Gaussian blur emerges in Figure 5 as the filter with the highest SSIM (0.8–1.0) and NCC (close to 1) values, indicating that it preserves much of the manuscript's original structure and texture. This high correlation suggests Gaussian Blur effectively reduces noise while maintaining key visual elements, making it ideal for applications that require minimal alteration to the manuscript's authenticity. Conversely, At the opposite end of the spectrum in Figure 5, the Sobel and Canny Edge filters produce very low SSIM and NCC values, indicating that they significantly alter the appearance of the manuscript by emphasizing edges rather than structural similarity. For ancient manuscripts, Sobel and Canny Edge may cause an exaggerated focus on high-contrast areas, often losing subtle textural details critical to the manuscript's authenticity.

Meanwhile, the adaptive threshold and Morphology filters in Figure 5 produce nearly identical SSIM values, ranging from 0.4–0.6 for SSIM and 0.6–0.8 for NCC, indicating a balance between structural retention and feature enhancement. Adaptive Threshold enhances the visibility of textual

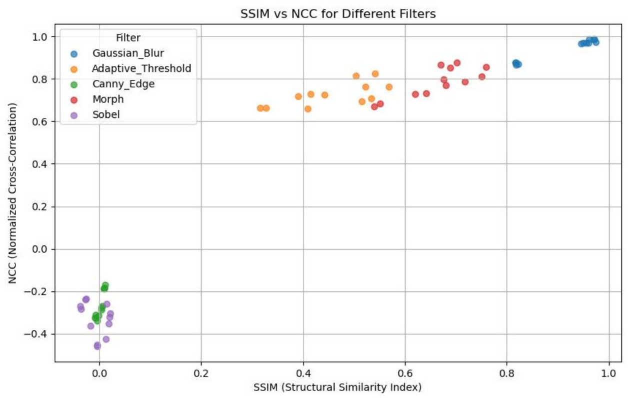

FIGURE 5. Scatter plot analysis for SSIM and NCC correlation.

elements by adjusting local contrast, which is particularly valuable for ancient manuscripts where fading ink or paper discoloration can obscure characters. Meanwhile, Morphology alters certain structural elements, often thickening lines or enhancing certain shapes, which can help highlight important features such as character boundaries. However, this filter may not fully preserve the original structure of the ancient manuscript.

V. DISCUSSION

Based on experiment results from five types of image processing techniques to improve image quality and structural integrity of ancient Javanese manuscripts, the results of this study highlight the effectiveness of the Gaussian blur method compared to the other four methods. This is by its theoretical application as a noise reduction method that maintains the primary structure [46]. Although this method is effective in structural preservation, its value in archiving is highlighted by the fact that it minimizes changes to the original features, which is important to ensure that digital replicas are similar to the original manuscript. In several previous studies, this method has been widely applied for pre-processing before the image is further processed.

In addition to the Gaussian method, this study also shows that the adaptive thresholding and Morphology techniques also show quite optimal values in producing significant readability improvements by increasing the contrast of ancient Javanese manuscript images. The ability of the Adaptive Thresholding filter to dynamically adjust contrast provides confidence in its effectiveness in restoring faded manuscripts. However, the trade-off in structural similarity, as shown by SSIM reduction, raises concerns discussed in the literature on thresholding techniques. These concerns indicate that there is a possibility of losing subtle structural features that are important for the authenticity of the interpretation. In this study, the contrast enhancement offered by Adaptive Thresholding makes it an ideal choice for preprocessing in Optical Character Recognition (OCR) tasks. However, contrast-based enhancement image processing such as binarization must be applied with caution in archival contexts to achieve a balance between readability and structural retention.

Meanwhile, the Morphology method that has a score between Gaussian and adaptive threshold in this study is considered a balanced approach because of its ability to highlight certain structural features while maintaining fundamental visual elements, thus bridging the gap between the readability and authenticity of ancient manuscript images. The role of Morphology filtering in improving readability without ignoring original features strengthens its potential as a compromise solution in digital preservation, where studies have shown that moderate contrast enhancement can make historical texts more accessible while retaining most of their original structural details.

In numerous prior research, the Gassian method has been widely applied for preprocessing to alleviate the limits of each technique before further image processing before the image is further processed by combining it with methods such as binarization or thresholding. The Gaussian method, which functions to reduce noise in images, is very useful in the binarization process of an ancient manuscript so that the desired characters are cleaner from existing degradation conditions. This aligns with Yahya's research, which demonstrates that Gaussian blur can significantly enhance the outcomes of the adaptive thresholding method [33]. In addition, ancient palm leaf manuscripts studied by Surinta and Chamchong also showed an increase in quality with the combination of Gaussian with the Otsu Global Threshold technique [51]. Furthermore, the Gaussian blur method was also employed as a pre-processing step before the modified Niblack local threshold technique, accompanied by Morphologyological post-processing [11].

The unsatisfactory outcomes produced by boundary-focused filters like the Canny Edge and Sobel algorithm demonstrate that their edge-centric results diverge from the visual fidelity of the book. The SSIM and NCC metrics, which emphasize the similarity between the processed results and the original pictures, indicate that these two filters yield poor scores. While these filters can enhance overall readability, they are more beneficial for specialized analysis than for preservation. Nonetheless, they have practical uses in identifying text outlines or structural imperfections. This aligns with research indicating that edge augmentation techniques may disrupt visual continuity, yet they are crucial for border identification. This renders them advantageous for tasks involving text identification and image segmentation amidst degraded objects.

VI. CONCLUSION

This study describes the various contributions of image processing filters to enhance legibility and maintain the structural integrity of ancient Javanese manuscripts, highlighting the need to use relevant digital techniques for their preservation. By evaluating five filters, the findings of the research affirm the significance of adaptable, objective-oriented approaches in digital preservation, particularly concerning filtering choices that support objectives such as maintaining structural authenticity and enhancing readability. In summary, Gaussian Blur is effective in archival tasks where visual authenticity is fundamental. This filter can also be useful for tasks such as segmentation, which require a balance between noise reduction and structural retention. Whereas, Adaptive Thresholding and Morphology significantly enhance legibility for future OCR procedures. Furthermore, while not ideal for comprehensive preservation, filters such as the Canny Edge and Sobel Algorithm are effective in edge recognition, potentially aiding in the identification of text borders or damage. This study will present a framework that harmonizes readability and authenticity to guarantee the preservation and accessibility of cultural assets for future inquiry and appreciation.

future research may adopt hybrid filtering methodologies that integrate the advantages of various filters to enhance both readability and structural integrity, such as combining Gaussian blur before applying other image processing techniques like Adaptive Threshold. Furthermore, several Machine learning techniques can be applied to manage complex damage effectively. In addition, combining subjective evaluations from cultural specialists with measurements beyond SSIM and NCC can provide a more complex and comprehensive assessment. Furthermore, expanding the scope of manuscript types and examining the impact of digital preservation on education and public participation will improve techniques for aligning accuracy and accessibility.

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